Tesis Doctoral presentada en la Universidad Miguel Hernández para la obtención del título de Doctor

Programa de Doctorado en Tecnologías Industriales y de Telecomunicación

Universidad Miguel Hernández de Elche

Cooperative Perception for Connected and Automated Vehicles using V2X Communications

Autor: Gokulnath Thandavarayan

Director: Prof. Javier Gozálvez Sempere

Codirector: Prof. Miguel Sepulcre Ribes

Fecha y lugar de la defensa:

Viernes día 26 de Mayo de 2023 a las 10:30 en el Salón de Grados del edificio Arenals

Abstract

Automated vehicles make use of multiple sensors to detect their surroundings. The sensing technology has significantly improved over the last years. However, the capabilities of on-board sensors like cameras, radars, or lidars are still limited under the presence of obstacles or adverse weather conditions, among other factors. Cooperative perception (a.k.a. collective perception or cooperative sensing) has been proposed to help mitigate these challenges by exchanging sensor data among vehicles using V2X (Vehicle-to-Everything) communications. V2X communications allow vehicles to exchange information about detected objects, and hence improve their sensing range beyond the capabilities of their local sensors thanks to cooperative perception. Cooperative perception can also help improve the vehicles' sensor detection accuracy and increase the confidence about the detected objects. It can also help mitigate the negative impact of adverse weather conditions or the negative effect of lighting conditions on the sensitivity.

ETSI and SAE are currently defining new V2X standards for cooperative perception. SAE has not yet published its standard. On the other hand, ETSI has published a Technical Report on collective perception that includes important aspects such as the Collective Perception Message (CPM) format and the message generation rules to decide when a new CPM should be generated and what information it should include. ETSI is now finalizing the standardization of the Technical Specification on collective perception. Industrial associations such as the C2C-CC and the 5GAA have included cooperative perception in their roadmaps. All these efforts highlight the industrial interest and potential of V2X communications to support the development and deployment of cooperative perception in connected and automated vehicles. Despite the advances made to date, the concept of cooperative perception is relatively new and an in-depth study of its operation and performance is required before considering its commercial deployment.

Cooperative perception allows frequent exchange of updates on the sensors detected objects to increase detection accuracy. However, the frequent updates increase the channel load on the communications channels, and pose a challenge for the scalability of the V2X communications network and the effectiveness of cooperative perception. In addition, they can generate high levels of object redundancy since many nearby vehicles can detect the same object and report it simultaneously. This simultaneous reporting of objects can improve detection accuracy to some extent. However, a high level of redundancy can overload the communications channel and affect the operation and effectiveness of the cooperative perception given the impossibility of transmitting critical messages due to the saturation of the communications channel. The general challenge in cooperative perception occurs mainly when the cooperative perception message is not well organized. It might be very inefficient to generate a cooperative perception message that contains a

small number of detected objects, which could also increase the load on the communications channel and affect cooperative perception.

This thesis extensively studies and evaluates the performance and operation of cooperative perception solutions and proposes different techniques to address the identified challenges, fulfilling the existing literature gaps. To this aim, the thesis presents first a dimensioning study to identify any inefficiencies in existing cooperative perception solutions and support the design of more advanced and scalable techniques. This dimensioning study evaluates the cooperative perception message generation rules proposed at ETSI and compares them with periodic generation policies to analyze its effectiveness and identify existing limitations. Then the impact of different sensor configurations, traffic densities and market penetration rates are analyzed in detail. The study also investigates the impact of congestion control on cooperative perception, since congestion control protocols can modify message generation and transmission when the radio channel is congested. ETSI has standardized a DCC (Decentralized Congestion Control) framework for V2X communications that spans over multiple layers of the protocol stack. To the author's knowledge, this is the first study that evaluates the combination of the ETSI defined DCC Access and DCC Facilities on cooperative perception. The study demonstrates the importance of the DCC configuration for the operation of the V2X network and the effectiveness of cooperative perception.

Based on the findings of the dimensioning study, different techniques are proposed in this thesis to mitigate the inefficiencies identified. This thesis mainly proposes two different techniques, namely the look-ahead technique and redundancy mitigation or control technique. The redundancy mitigation proposal is designed to reduce the redundancy in the network by filtering the detected objects reported in cooperative perception messages that have not significantly changed their position, speed, and heading since the last time they were received as part of a cooperative perception message from other vehicles. The evaluation shows that the proposed redundancy mitigation technique significantly reduces the redundancy and channel load without degrading the perception for safety-critical short and medium distances. The Look-Ahead proposal reorganizes the transmission of objects in the cooperative perception message. It includes objects in the current cooperative perception message that are predicted to be included in the following cooperative perception message. This reorganization results in vehicles transmitting fewer messages, and each message includes information about a higher number of detected objects. This approach reduces the communications overhead and the channel load, and improves the perception. Finally, the thesis proposes methods to combine the proposed techniques (Look-Ahead and redundancy mitigation) to further improve the effectiveness of cooperative perception and the system's scalability. The different combinations are evaluated with and without DCC, and the conducted study shows that combining the two proposals can further reduce the channel load and improve the scalability of cooperative perception services without degrading the perception.